

MODELLING AGRICULTURAL PRODUCTION SYSTEMS USING AN ACTION-FLOW-STOCK ONTOLOGY

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ABSTRACT

This contribution depicts an approach enabling agricultural production systems to be represented at various spatial-temporal scales and organization levels: single plot or workshop, whole farm, group of farms within a territory, supply chain. This approach is based on an 'Action-Flow-Stock' ontology according to which each production unit is represented by a stock subject to filling-emptying actions controlled by conditions derived from states or events locally observed on some processes. Whereas stocks are computed as continuous variables, actions are represented by dynamical discrete functions. The models built with this ontology, whatever the formalization framework used to implement them (systems dynamics, multi-agents systems, timed automata), aim at dynamically simulating both the material flows and the human activities within agricultural production systems. The intended use of such models is to help agricultural stakeholders design and assess actual or potential management strategies in the light of the new concerns brought by the sustainability issues.

Keywords: Hybrid dynamical systems; Action representation; Agricultural production systems simulation; Integrated impact assessment.

1. INTRODUCTION

Our approach meets the objectives traced by Thornton and Herrero (2001) about mixed crop-livestock production systems to deal with the challenges brought by the needs to develop food production in the next decades worldwide. According to these authors, a modelling framework is necessary to assess the impacts of the various change factors agricultural systems are increasingly subject to. What they call for is, actually, building simulation models to support agricultural stakeholders design and assess 'attainable' (in practice) management strategies rather than, simply, 'feasible' (in theory) strategies.

With this aim, Thornton and Herrero (2001) established a long list of requirements this modelling framework should fulfil among which its capacity of representing agricultural actual practices is first place. According to these authors, this is the criterion that best defines models' applicability. In effect, the issues the farmers are facing to have more a systemic dimension than a mere technical one. Management is thus considered as the key-factor of agricultural complexity and

one of the most challenging research issues (Thornton and Herrero, 2001). But taking into account actual human practices in production systems models, namely in agricultural ones, is precisely the missing point (Garcia et al., 2005).

Therefore, one of the major scientific stakes is methodological. What has to be built is a modelling framework allowing one to:

- represent a production system at different scales and levels of analysis;
- integrate the various pieces of knowledge multiple stakeholders have on this system;
- simulate the dynamics of interactions between human activities and material flows;
- assess the impact of actual practices on the viability and sustainability of the system;
- design and test new management strategies with agricultural stakeholders to improve the overall system's performances according to various criteria.

Some of our recent achievements go clearly in this direction:

- designing flow management models at the sub-farm level (Guerrin, 2001; Courdier et al., 2002; Guerrin, 2004; Hélias et al., 2008);
- integrating biophysical and flow management partial models at the whole-farm level (Vaysières, 2008);
- devising a generic action modelling framework (Guerrin, 2005);
- integrating all this modelling endeavour within a global approach.

Whatever the formalism they rely on (systems dynamics, multi-agents system, timed automata), our models share common ontology and objective: simulating material transfers among a set of production units (PU's) represented as stocks subject to filling or emptying actions so as to answer stock management questions:

- Who? (which PU should transfer its material?)
- Where? (towards which other PU?)

- When? (with respect to which schedule or event?)
- How? (with which vehicle, workforce, resource?)
- How much? (what quantity?).

How agricultural production systems can be represented using the ‘Action-Flow-Stock’ (A-F-S) ontology common to all of our models, what do these models look like and what they are used for is presented in this article.

2. ACTION-FLOW-STOCK MODELLING

2.1. Production unit

Every agricultural production system may be represented as a set of more or less elementary PU’s linked by material flows of different natures. Each PU is a stock with an inflow, an outflow and, possibly, an overflow (Fig. 1).

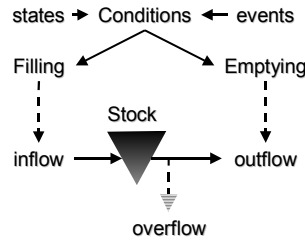


Figure 1: Action-Flow-Stock Representation of an Elementary Production Unit

It is classically represented as a continuous variable by a mass-balance differential equation:

$$\frac{dV(t)}{dt} = Q_{in}(t) - [Q_{out}(t) + Q_{over}(t)] \quad (1)$$

Material transfers from one PU to another are realized thanks to filling or emptying actions encoded as binary variables (either they occur or not) subject to time-varying constraints and conditions $C_A(t)$:

$$s_A(t) = \begin{cases} 1 & \text{if } C_A(t) \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where $s_A(t)$ denotes the binary state function of an action A . It thus exhibits a rectangular time evolution in which each pulse, accounting for the realization of action A , is characterized by its start date, end date and duration (Fig. 2).

Encompassing both continuous and discrete variables, the models based on this ontology belong to the family of hybrid dynamical systems (Antsaklis et al., 1998).

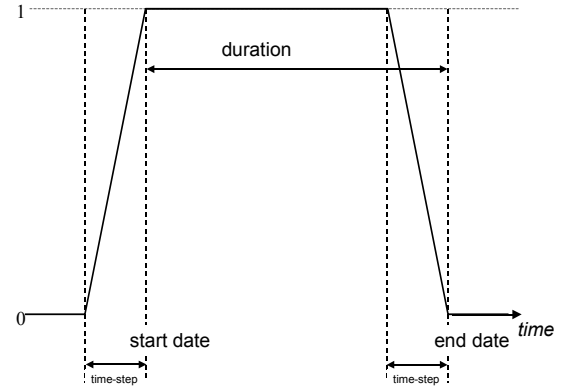


Figure 2: Singular Action Realization

2.2. Action course

As stated by Eq. (2) and sketched in Fig. 2, every action is described as a binary dynamic process subject to a realization condition: its state is 1 whenever $C_A(t)$ is true or 0 when it is false. The action state function defines a partition of the temporal domain between the periods when action is realized and those when it is not. The realization condition of every action is defined by the combination of elementary conditions relative to the states of various processes (clocks, schedules, observations, other actions), continuous or discrete, upon which relevant events for triggering or inhibiting action are detected. These are these events which determine the start and end dates of action realizations by altering the evaluation of their condition. When the condition is no more satisfied while action is ongoing it stops.

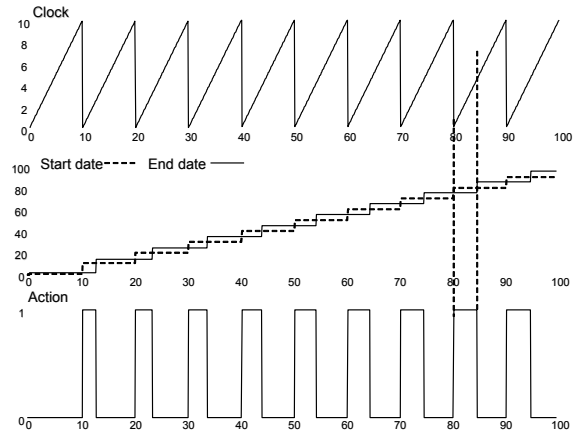


Figure 3: Clock (top), Start and End Dates (middle) and Action Course Evolutions

Figure 3 illustrates how an action course may be simulated using the following concepts:

- Observed process: here a clock, encoded as a piecewise linear function, is taken.
- Events prior to action (EPA): here the time points at which the clock function is zero (clock ticks), though it could be also any state value of any other process.
- Start dates: time points determining each pulse after an EPA, possibly complying with the

conjunction of various constraints such as disturbances (rainfalls,...), resource availabilities (material, workforce, vehicle...), management rules (e.g., delay, postponement).

- End dates: time points derived either from an absolute time-varying duration (like in Fig. 3) or from events detected upon processes (like for the start dates).
- Management rules: specifying the quantities to be transferred, the priorities among actions, logistic constraints (payload, transportation delay,...).
- Action course: encoded as a binary dynamic state function as in Eq. (2).

An action is converted into effects by combining (e.g., by making the product of) its state function with a base flow (e.g., working time available daily, filling rate of a tank). This flow may vary over the action course to represent some progressiveness in the effect or depend upon other processes to represent the modulation of the effect according to the action context.

2.3. Complex activities

Activities are sets of coordinated actions. Figure 4 gives an example where an action *A* (from the example given in Fig. 3) fills a stock whereas an action *B* empties it so that the stock level $V(t)$ remains between an upper and a lower threshold.

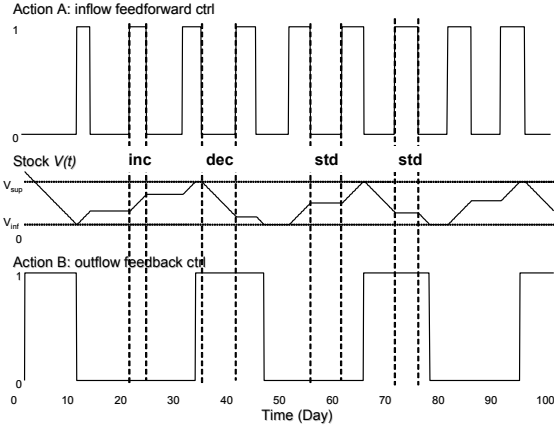


Figure 4: Simulating an Action *B* Indirectly Derived from an Action *A* to Control the Stock Level $V(t)$ between Thresholds V_{sup} and V_{inf} (inc: increase; dec: decrease; std: steady)

It is assumed both inflow and outflow are the same and constant. For this reason (see Fig. 4), whenever:

- *A* is on and *B* is off, then the stock increases;
- *A* is off and *B* is on, then the stock decreases;
- $A = B$, then the stock is steady.

Specifying an action directly as a function of another action so that both satisfy some temporal relation is also possible. This is done by setting the constraints on their start dates and durations derived from the Al-

len's (1984) temporal relation that should hold among them: BEFORE, MEETS, OVERLAPS, DURING, STARTS, FINISHES, EQUAL or their inverses. For example (see Fig. 5), specifying an action *E* according to an action *D* so that *E* is on during *D* (i.e., $DURING(E,D)$ holds) implies *E* starts after *D* and its duration does not exceed that of *D*. It is thus possible to specify complex activities made of sets of coordinated actions as that of Figure 5.

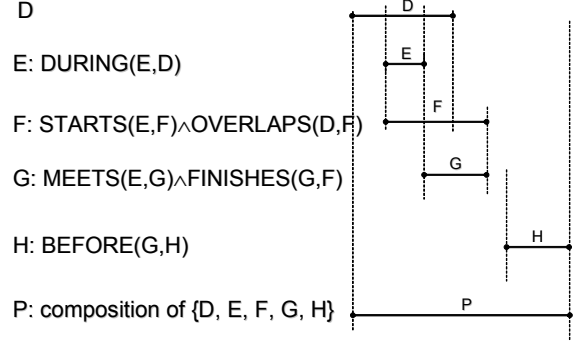


Figure 5: Specification of a Set of Coordinated Actions using Allen's (1984) Temporal Relations

In the case of interruptions (deterministic or random), the realizations of actions can be cancelled, interrupted, resumed, while their total duration is kept by the means of local feedback controllers.

Action courses composing an ongoing activity can be interpreted as external processes by identifying the Allen's relation holding between any two of them. This is done by verifying the temporal order of their start and end dates for each Allen's relation. For example, in Figure 5, the relation $DURING(E,D)$ can be observed if *E* has started after *D*, is already achieved, and *D* is still being pursued. This comes down to evaluate the proposition: $t_D^+ < t_D^- < t_E^- < t_E^+$, where t_i^- and t_i^+ are the start and end dates of action *i* respectively.

Action realization conditions, action state functions and temporal relations between actions are all represented by dynamic binary functions. These functions may be interpreted as truth values of timed logical propositions: their simulation interval is dynamically partitioned into periods with value 0 (false) or 1 (true). Using the Boolean algebras $\langle \{0,1\}, +, \times \rangle$ or $\langle \{0,1\}, \max, \min \rangle$, it is easy to define operations on action state functions equivalent to the classical logical connectives (NOT, AND, OR, XOR). This allows logical reasoning about action or, more generally, situations they are part of, to be simulated in order to derive new actions and new situations. For example, Figure 6 describes the three possible actions, specified in terms of both actions *A* and *B*'s state functions, that could be derived to account for the logical equivalences of the three cases enumerated above about the stock evolution in the example given Figure 4:

- stock $V(t)$ increases whenever *A* and not *B*;

- stock $V(t)$ decreases whenever not A and B ;
- stock $V(t)$ is steady whenever either A and B or not A or B .

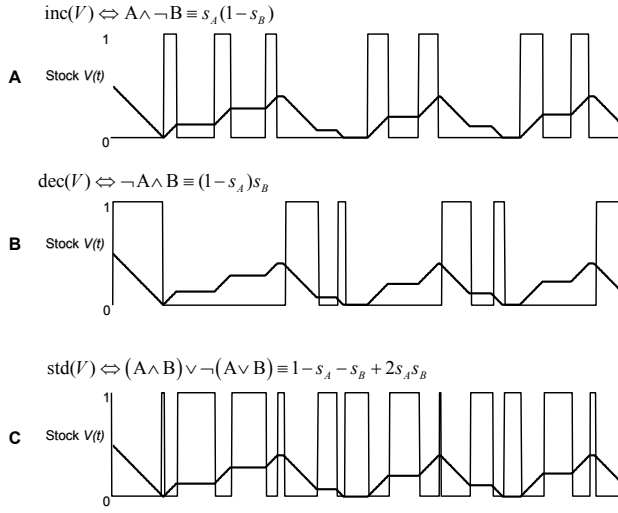


Figure 6: Deriving the Possible Actions According to the Three Logical Combinations of Actions A and B Controlling the Inflow and Outflow of Stock $V(t)$

2.4. Agricultural production system

Actual agricultural production systems may be represented at several organization levels (single field or workshop, whole-farm, group of farms in a territory, agricultural supply chain) as networks of A-F-S units exhibiting various configurations according to the real case to be accounted for (see examples in section 3).

Two types of flows are distinguished according to whether they result from man-driven or natural processes: “workable flows”, occurring only when man intervenes, and “biophysical flows”, occurring even in absence of human intervention. Both types of flows interact by the means of human activity which aims at influencing the biophysical flows leading to the system’s products and impacts by the means of the workable flows it generates.

The management of an agricultural production system may thus be seen as controlling a set of stocks by the means of farming activities. These, fundamentally, are exerted within a dynamical environment, evolving independently of any action, making crucial taking account of time irreversibility in management. These activities stem from the confrontation between the actual situations encountered by the farmer and the management strategies he/she has devised to deal with.

By “situation”, it is meant the set of constraints of different natures (resource availability, climate or economical conditions,...) exerted at given time and location which restrict the panel of action possibilities.

Among the “resources” necessary to action, information intervenes in the form of events, either endogenous (state transitions) or exogenous (disturbances or climatic, economical, political, social, regulatory constraints), perceived by the farmer directly or indirectly (i.e., by the means of indicators).

By “strategy”, it is meant the combination of general principles of acting and making decisions about the workable flows. A strategy reflects, even these are not easy to characterize, the farmer’s knowledge, preferences, objectives and management abilities (interpretation, reactivity, decision, anticipation, experience).

Situations and management strategies are interdependent: implementing strategies contributes to create new situations that, in turn, influence the design of new strategies according to the outcome gained from practical implementations.

3. APPLICATIONS

Based on the ‘Action-Flow-Stock’ ontology described above, we have built in the recent years several simulation models to deal with specific agricultural production systems. All these models illustrate the capabilities of the A-F-S ontology to cope with production unit networks exhibiting various configurations.

3.1. Magma: livestock effluent management at the farm level

The Magma model (Guerrin, 2001) addresses the case of livestock effluent management within a farm. Two types of units are involved in such a “distribution” (i.e., one-to-many) configuration (Fig. 7): livestock enterprises producing animal wastes and consumption units, such as crop plots or waste treatment plants, where effluents may be spread over or supplied.

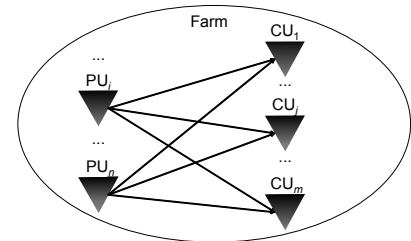


Figure 7: Distribution Configuration of Material Flows at the Farm Level in the Magma simulation Model (PU: livestock enterprise; CU: consumption unit)

Simulating Magma allows management strategies of livestock effluents to be assessed with respect to several indicators: environmental (nitrogen losses due to stock overflowing, fallow land spreading, or crop over fertilization); agronomical (nitrogen applied to crops); economical (working time, vehicle mileages,...) and organizational (frequency and temporal distribution of spreading actions).

3.2. Biomass: livestock effluent management at the territory level

Extending the Magma capabilities over a whole territory encompassing several farms, the Biomass agent-based simulation model (Courdier et al., 2002) addresses the case of livestock effluent transfers between distinct farms (Fig. 8): farms with excess of effluent with respect to the absorption capacity of their own

crops; farms with deficit of organic matter with respect to their own production capacity. Biomass also allows intermediate storage facilities or effluent treatment plants to be added to the network. Biomass puts into play several hundreds of distinct agents (farmers, livestock enterprises, crop plots, vehicles,...) in real-scale applications. These agents, characterized by numeric or symbolic attributes, interact dynamically according to their roles: producer, consumer, organic matter carrier.

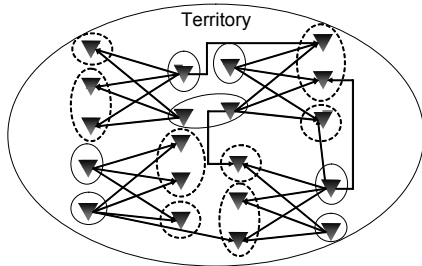


Figure 8: Distribution Configuration of Material Flows in the Biomass Multi-Agents System (full lines: effluent production units in surplus farms; dotted lines: consumption units in deficit farms)

3.3. Approzut: supply of a collective treatment plant by multiple farms

The Approzut model (Guerrin, 2004) deals with the case of simulating the flows in a two-stage production system where the first stage is a set of pig farms producing slurry and the second stage is a collective treatment plant where this slurry is brought in a many-to-one fashion (Fig. 9). The strategy assessment is here mainly done in terms of organization and logistics.

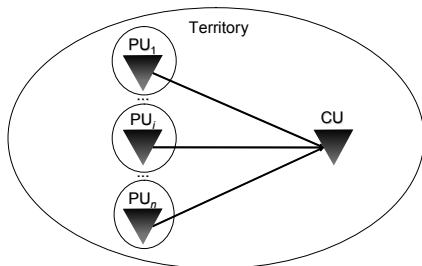


Figure 9: Supply Configuration of Material Flows at the Territory Level in the Approzut Simulation Model (PU: livestock farm; CU: single waste treatment plant)

3.4. MagmAppro: mixed distribution/supply configuration connecting two remote territories

MagmAppro (Lopez-Ridaura et al., 2007) results from coupling together the Magma and Approzut models. It is used to simulate an effluent management collective plan to be implemented in Brittany (Western France) involving dozens of pig farms and crop farmers located about 40kms one from each others (Fig. 10). Coupled with biophysical models, MagmAppro allows namely the impact of such plans to be assessed as nitrogen and methane volatilized at storage and spreading in addition with other indicators as in Magma and Approzut.

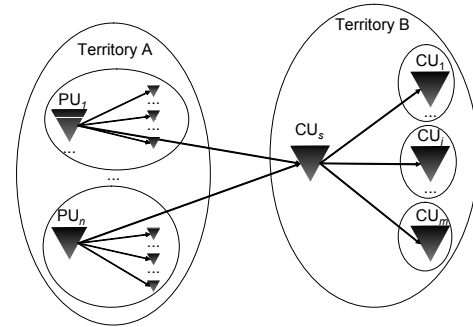


Figure 10: Mixed Distribution/Supply Configuration of Material Flows Connecting Two Remote Territories in the MagmAppro Simulation Model (PU: livestock farms encompassing livestock enterprises and crop plots; CU_s: intermediate stock; CU: crop farms)

3.5. Gamede: global Activity-Flow-Stock model at the whole-farm level

The Gamede model (Vayssières et al., 2007) addresses the case of managing all the material flows (vegetal and animal biomasses and products, nitrogen, water,...) and 19 technical activities (harvesting, fertilising, spreading, feeding, milking,...) at the whole-farm level assessed by several sustainability indicators (Fig. 11).

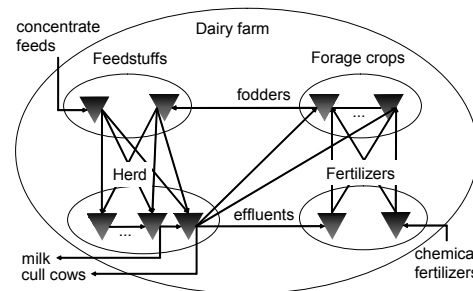


Figure 11: Dairy Farm in the Gamede Simulation Model Viewed as Four Interconnected Sub-systems Encompassing Several A-F-S Production Units

3.6. PigSC: pig industry supply chain in Reunion Is.

Modelling the whole pig industry in the Reunion Island using the A-F-S ontology is being done to represent the pig production chain from the raw feedstuff suppliers to the pig products retailers, passing by the ~200 rearing enterprises in the whole-Reunion island (Fig. 12).

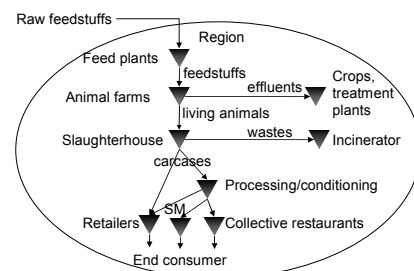


Figure 12: The Pig Industry in the Reunion Island Viewed as a Supply Chain (SM: supermarkets)

This model aims at simulating the material flows and coordination among stakeholders. It could be used later to support Life Cycle Analyses of the pig industry.

4. CONCLUSIONS AND FUTURE PROSPECTS

As far as we have experienced it, the A-F-S ontology has proved useful to represent and simulate, at various scales and organization levels, agricultural production systems viewed as sets of interacting biophysical and human-driven processes. In contrast with most decision-support models in agriculture, human activity is explicitly represented. This is deemed crucial as what is wanted is to assess the sustainability of agricultural production systems. In effect, it is by representing at best what is actually done by the farmers, when and how it is done, that one can simulate impacts realistically (e.g., consuming resources, emitting pollutants). In turn, it is possible to assess the reciprocal influence of the context so modified on the course of action itself.

Our tentative action modelling framework (Guerrin, 2005) needs still be generalized to a wider class of production systems and completed with additional features so as to simulate the various means actual actors use to coordinate their activities. Two other issues of major interest for the practical use of our models are still to be further investigated:

- environmental assessment of agricultural production systems at multiple scales and the correlative choice of relevant representational granularities of the model(s) to be used (Lopez-Ridaura et al., 2007);
- participatory use of such models in virtual experiments with agricultural stakeholders involved in actual decision processes (Médoc et al., 2004).

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